DETERMINISTIC APPROACH FOR DESIGN FLOOD ESTIMATION: THEORY AND PRACTICE

Joko Sujono*)

ABSTRACT

Design flood estimation with certain average recurrence interval (ARI) is a first step in designing hydraulic structures. Inaccuracies in design floods may have a great effect, not only from an economic point of view, but also for human life. The determination of the design flood with a reliable results is not an easy task. Due to the difficulties in exaggerating the complex process of hydrology phenomena, deterministic approach is commonly used for design flood.

The deterministic approach, however, should not be used for design flood estimation since there are several uncertainties inherent in this approach and the assumption commonly used, that the rainfall with certain ARI will produce a flood with the same ARI is not valid.

INTRODUCTION

Design floods are required for sizing hydraulic structures such as culverts, spillways, and for flood plain management. A design flood estimation method that produces the highest accuracy of, and most confidence in, the flood quantile is needed because less accurate and less reliable results in flood design estimation may have a deleterious effect on economics as well as human life.

The selection of the most appropriate design flood method has traditionally not been an easy task. A number of methods have been developed and applied to flood estimation but the results of each method are not always of the same magnitude, and can be significantly different. In addition, floods like other hydrologic processes, occur randomly; they follow the law of chance and are time-dependent for the sequence of occurrences involved (Chow 1964).

Difficulties arise in simulating the stochastic processes of hydrologic phenomena, because they are time and chance dependent. Two approaches are commonly used for flood design: the deterministic and the probabilistic. In this paper, however, only the characteristic of the most common approach for design flood estimation ie. the deterministic approach, is presented and analysed. By analysing the concepts used and the possible outcomes, the suitability of the approach for design flood estimation can be determined.

DESIGN FLOOD REQUIREMENTS

It is important to differentiate between two common words in engineering hydrology ie. forecasting and prediction. Conceptually, there is a big difference in engineering application between flood forecasting and prediction. Clarke (1973) used the term forecasting as simulated hydrographs of specific future events with respect to real-time to be used in making operational decisions (real-time forecasting). Whereas, prediction refers to simulated hydrographs without specific time reference that are intended to be used for the purposes of engineering design (flood design).

McDermott and Pilgrim (1982) defined design flood estimation as the estimation of the flood quantile or flood magnitude with specified ARI or return period, at a site on a particular stream which is expected to be equaled or exceeded on an average number of times in a given time interval. By looking at this definition, it is clear that there are two values which should be taken into consideration in design flood estimation ie. a flood magnitude (flood peak, volume etc.) and its ARI.

THEORY

The deterministic approach is an extreme simplification of the complexity of natural phenomena by using a set of algorithms to mimic the hydrologic processes involved in the transformation of input into output. In the deterministic approach, the chance of occurrence of the hydrology phenomena is ignored and the approach follows laws of certainty (Chow 1964). The deterministic approach is an input-system-based approach; given values of initial and boundary conditions (parameters) of the system, a set of input values will always produce exactly the same output values (see Figure 1).

Figure 1 Concept of the deterministic approach (modified from O'Loughlin 1994)

Numerous deterministic methods for flood estimation have been developed and used including the conventional Rational Method, the unit hydrograph method and runoff-routing methods, ranging from simple conceptual models to complex physically based models. With the exception of the Rational Method, most of the deterministic methods can produce not only peak discharge but also complete hydrograph needed for designing major hydraulic structures.

The deterministic models can be used either for flood forecasting or flood design. In the application of

*) Ir. Joko Sujono, M.Eng., Dosen Jurusan Teknik Sipil Fakultas Teknik UGM

the deterministic methods for flood design, it is must be assumed that design rainfall, as an input of the system, will produce a flood as an output of the system with the same ARI as the input. Since both flood magnitude and its ARI are needed in the design flood, unless the assumption of ARI transference can be shown to be valid in practice.

PRACTICE

Uncertainty in the deterministic approach

Generally, flood estimation methods that are based on the deterministic approach requires three types of data ie. input data (eg. rainfall), variable catchment data (eg. antecedent conditions), and fixed catchment data (eg. catchment area). In terms of quality and quantity of the data available, the input data (rainfall) is normally regarded to be of higher quality than output data (streamflow). As a result, design floods based on the input data are widely used, especially for designing water projects with low probability of failure. In the application of the deterministic approach to flood design, however, there are some sources of error which may lead to the uncertainty of resulted flood estimate (Tung and Mays 1980; Kuczera 1988; National Research Council 1988).

a. input data error

Because of the lack of perfect hydrographic information (eg. measurement errors) there is uncertainty inherent in the input data. Osborn et al. (1982) pointed out that rainfall characteristics are fundamental inputs to hydrologic models to simulate runoff characteristics. The errors in the estimation of precipitation input may result in serious errors in predicted streamflow hydrograph (Beven and Hornberger 1982; Malone and Cordery 1989). Kuczera and Williams (1992) evaluated the effect of errors in the temporal and spatial distribution of rainfall on the uncertainty of calibrated rainfall-runoff parameters in the RORB model. They found that, if allowance is made for uncertainty in the calibration event rainfall, the uncertainty in the calibrated parameters increases drastically about 100% on the 90% prediction interval of the 100-year design flood as shown in Figure 2.

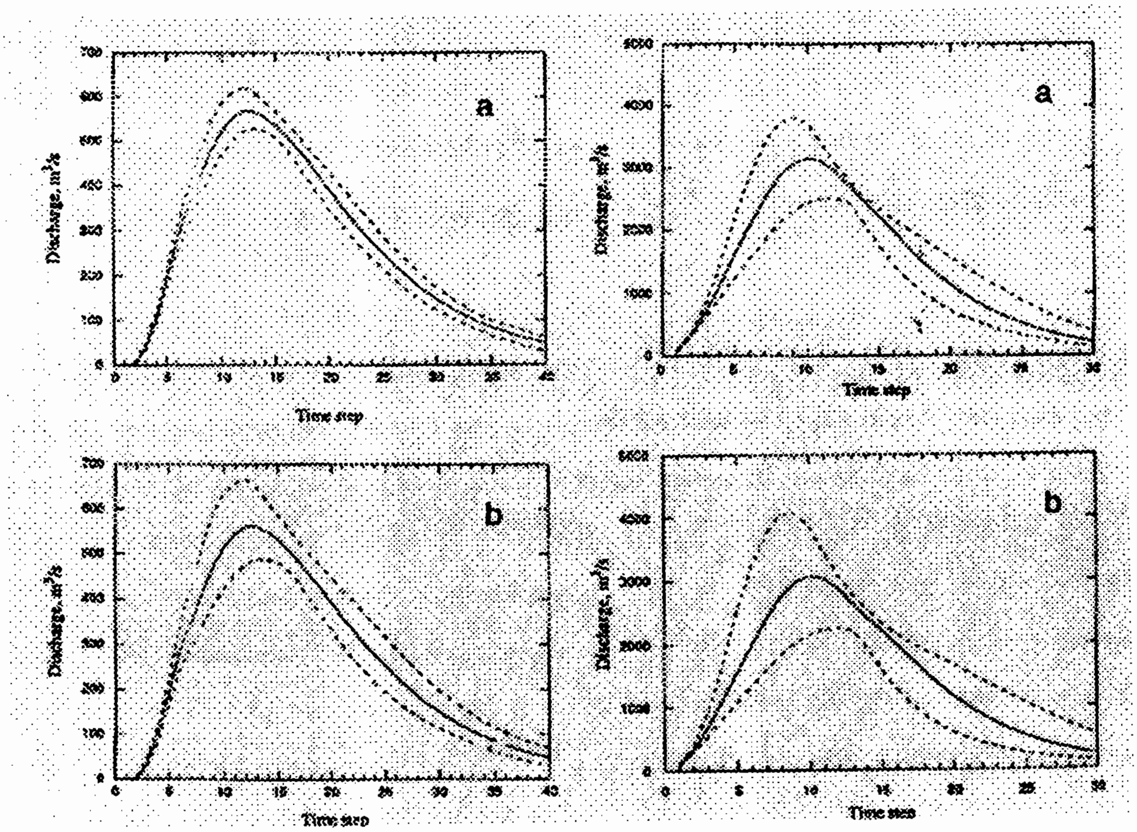

Figure 2 The 1-hour 100-year and PMP design hydrographs and its 90% prediction limits
(a) assuming no uncertainty in sub-areal rainfall and
(b) assuming uncertainty in sub-areal rainfall
(after Kuczera and Williams 1992)

b. model error

Model error results in the inability of the model to predict runoff accurately, even given correct inputs and parameter estimates. The model error is due to the fact that the model is only an approximation of the natural behaviour. In addition, inappropriateness of the model to the problem under question is also another source of the model error (Melching et al. 1990).

c. model parameter error

For model calibration, parameter values obtained from calibrations of individual events vary from event to event; there is no a set unique parameter estimate (Beven 1993). Parameter error occurs due to an average value usually being adopted for design. By using the mean value, part of the information is lost. As a result, the outcome of the model simulation may give a result which has not or cannot occur in practice. An example is in the use of the average unit hydrograph in flood design. The use of averaging value is one of the causes of errors in flood prediction (Malone and Cordery 1989). For models with physically based parameters, parameter errors result from the inability to take into account spatial and temporal distribution on the basis of point measurements.

Uncertainty analysis

Uncertainty due to input data error, parameter error and model error may propagate to the output, yielding considerable uncertainty about the design flood. Some research has been done to analyse the uncertainty in hydrologic models but not all the sources of uncertainty have yet been covered. Most of analyses have been directed towards the effect of parameter uncertainty on model performance (eg. Garen and Burges 1981; Melching et al. 1990; Harlin and Kung 1992; Melching 1992). An example of the result of uncertainty analysis are shown in the Figure 3. This figure shows that the uncertainty of deterministic models as a result of parameter uncertainty can be very large; the implications for the associated ARIs can only be guessed.

Validity of the assumption used

The most common way of using deterministic models in design is by converting a design rainfall with a selected ARI to produce a flood with the same ARI by means of a catchment model. In reality, however, the assumption that the ARI of the design hydrograph is equal to the ARI of the design rainfall has never been proven to be valid in theory or practice. As a result of model boundary conditions such as antecedent conditions and simplification (lumping) of factors such as spatial and temporal variability of rainfall, it is unlikely that the rainfall and peak discharge have the same ARI (eg. NERC 1975; Sri Harto 1985; Qian 1987; Bradley and Potter 1992). Cordery (1971) in his study using catchment unit hydrographs found that flood peaks generally had a greater ARI than the design rainfall. NERC (1975), on the other hand, found the opposite. Sri Harto (1985) in his study using 30 catchments in Java-Indonesia found that there is no equality between ARI of rainfall and runoff as shown in Figure 4. In fact, in real storms there may even be inverse relationship between rainfall ARI and flood ARI indicating a systematic catchment effect on ARI.

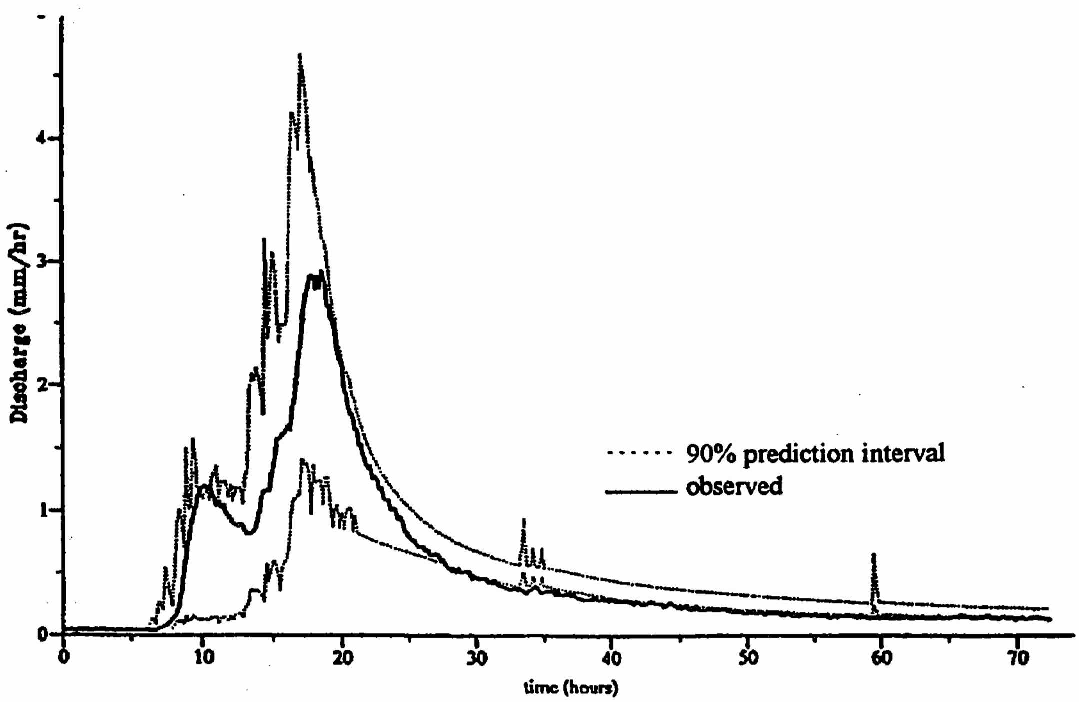

Figure 3 Results of the uncertainty analysis of the TOPMODEL simulations of the Maimai catchment, New Zealand (after Beven 1993)

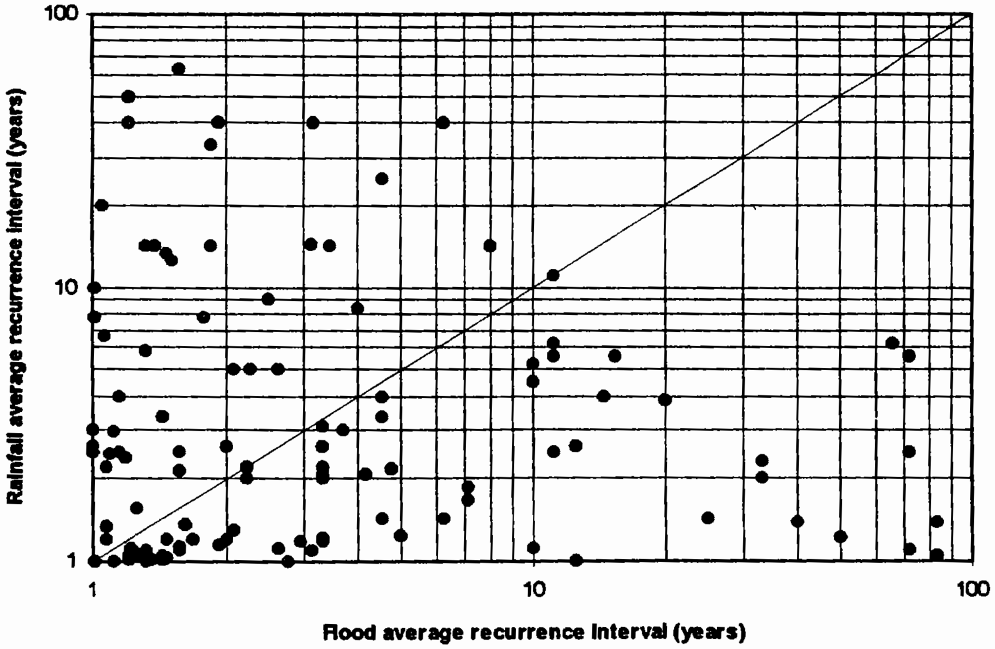

Figure 4 Relationship between ARI of flood and rainfall for individual storm events (after Sri Harto 1985)

DISCUSSION

By looking the theory and practice of the deterministic approach for flood design, several important issues become apparent.

1. The deterministic approach is generally using various type of data such as rainfall, catchment characteristics. By using more variables outside the streamflow data set, however, more uncertainty is produced in the deterministic approach. Uncertainty is compounded by model parameters and model errors which, because they are difficult to quantify, results in the accuracy of design floods estimated by the deterministic approach being essentially unknown and unknowable.
2. The deterministic approach is fundamentally unable to produced flood magnitudes with known ARIs; the two unseparable requirements for hydrologic design.
3. The deterministic approach cannot account for all causative factors involved in the future outcome of hydrologic random phenomena (Yevjevich 1972). No matter how complicated a representation of the system physics, no model will ever be able to mimic the hydrologic process as well as it occurs in nature (James and Burges 1982). This phenomenon can be seen as expression of the principle of Occam's Razor - that complex physically-based models often produce no better or even less accurate results than simple ones (Loague and Freeze 1985; Chiew et al. 1993; Michaud and Sorooshian 1994).
4. The determination of parameters in deterministic models is by calibration on several historical flood events. Since hydrology processes are essentially stochastic, chance dependent and time-dependent, it must be expected that each calibration event will yield different parameters; that is, there is no unique parameter estimate that can reproduce all recorded runoff events whether historical, forecast or for design (Loague and Freeze 1985; Beven 1993). Matching observed and forecasted response does not necessarily mean matching catchment response (James and Burges 1982) especially in the ARI domain.
5. The use of an average set of parameters may produce a design flood which suffers not only from less of information by averaging, but possibly loss of relevance because the average parameters cannot occur in combination. The deterministic approach does not represent the full information available in the hydrologic data. Deterministic solutions of hydrologic problems most often use the mean value of random variables as the value of main parameters, so much information is lost.

CONCLUSIONS

The deterministic approach should not be used for flood design because the assumption that design rainfall will produce flood with the same ARIs is invalid. As a result, the ARIs of design floods are unknown. In addition, the accuracy of any flood magnitude from deterministic models is also unknown because of uncertainty with input data, the model, the model parameters and model boundaries (eg. initial condition).

A catchment response function for hydrological design which preserves the ARI of the design rainfall with the design flood, not a representation of physical cause and effect, may be needed.

REFERENCES

Beven, K., 1993, Prophecy, reality and uncertainty in distributed hydrological modelling, *Advances in Water Resources,* 16, 41-51.

Beven, K.J. and Hornberger, G.M., 1982, Assessing the effect of spatial pattern of precipitation in modeling stream flow hydrographs, *Water Resources Bulletin,* 18(5), 823-829.

Bradley, A.A., and Potter, K.W., 1992, Flood frequency analysis of simulated flows, *Water Resources Research,* 28(9), 2375-2385.

Chiew, F.H.S., Stewardon, M.J. and McMahon, T.A., Comparison of six rainfall-runoff modelling approaches, *Journal of Hydrology,* 147, 1-36, 1993.

Clarke, R.T., 1993, A review of some mathematical models used in hydrology with observations on their calibration and use, *Journal of Hydrology,* 19, 1-20.

Chow, V.T., 1964, Statistical and probability analysis of hydrologic data, part I: frequency analysis, in *Handbook of Applied Hydrology,* edited by V.T. Chow, McGraw-Hill, New York.

Cordery, I., 1971, Estimation of design hydrographs for small rural catchments, *Journal of Hydrology,* 13, 263-277.

Garen, D.C. and Burges, S.J., 1981, Approximate error bounds for simulated hydrographs, *Journal of Hydraulic Division,* ASCE, 107(HY11), 1519-1534.

Harlin, J. and Kung, C-S., 1992, Parameter uncertainty and simulation of design floods in Sweden, *Journal of Hydrology,* 137, 209-230.

James, L.D. and Burges, S.J., 1982, Precipitation-runoff modelling: future directions, in *Applied Modelling in Catchment Hydrology,* edited by V.P. Singh, pp. 291-312, Water Resources Publication, Littleton, Colorado.

Kuczera, G. and Williams, B.J., 1992, Effect of rainfall errors on accuracy of design flood Estimates, *Water Resources Research,* 28(4), 1145-1153.

Kuczera, G., 1988, On the validity of first-order prediction limits for conceptual hydrologic models, *Journal of Hydrology,* 103, 229-247.

Loague, K.M. and Freeze, R.A., 1985, A comparison of Rainfall-runoff modelling Techniques on small catchments, *Water Resources Research,* 21(2), 229-248.

Malone, T.A. and Cordery, I., 1989, An assessment of network models in flood forecasting, in *New Directions in Surface Water Modeling,* edited by M.L. Kavvas, pp. 115-124, IAHS Publication 181.

McDermott, G.E. and Pilgrim, D.H., 1982, *Design Flood Estimation for Small catchments in New South Wales,* Australian Water Resources Council, Technical Paper No. 73, Australia Government Publishing Service, Canberra.

Melching, C.S., 1992, An improved first-order reliability approach for assessing uncertainties in hydrologic modelling, *Journal of Hydrology,* 103, 157-177.

Melching, C.S., Yen, B.C. and Wenzel, H.G.Jr., 1990, A reliability estimation in modelling watershed runoff with uncertainties, *Water Resources Research,* 26(10), 2275-2286.

Michaud, J. Sorooshian, S., 1994, Comparison of simple versus complex distributed runoff models on midsized semiarid watershed, *Water Resources Research,* 30(3), 593-605.

National Research Council (US), 1988, *Estimating Probabilities of Extreme Floods: Methods and Recommended Research,* National Academic Press, Washington.

Natural Environment Research Council (NERC), 1975, *Flood Studies Report,* Vol. I. NERC, London.

O'Loughlin, G., 1994, *Note on Engineering Hydrology,* School of Civil Engineering, University of Technology, Sydney.

Osborn, H.B., Lane, L.J., Richardson, C.W. & Molnau. M.P., 1982, Precipitation, *in Hydrologic Modeling of Small Watersheds,* edited by C.T. Haan, H.P. Johnson and D.L. Brakensiek, pp. 81-118, American Society of Agricultural Engineers, Michigan.

Qian, W.C., 1987, Analysis of the design storm time-intensity pattern for medium and small watersheds, *Journal of Hydrology,* 96, 305-317.

Sri Harto Br., 1985, A study of the unit hydrograph basic characteristics of rivers on the island of Java for flood estimation, Ph.D. Thesis, Gadjah Mada University, Yogyakarta.

Tung, Y-K. and Mays, L.W., 1980, Risk analysis for hydraulic design, *Journal of the Hydraulics* Division, ASCE, 106(HY5), 893-913.

Yevjevich, V., 1972, *Probability and Statistics in Hydrology,* Water Resources Publications, Fort Collins, Colorado.